APex™ SOLAR CELL MANUFACTURING

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ABSTRACT

APex™ solar cells are a low-cost solution for solar electric power generation. Recent progress has been made in the areas of process definition and equipment development, as well as furthering the understanding of the material quality APex™ production system generates sheets of polycrystalline silicon in a continuous in-line process. The APex™ sheet growth system has evolved through five design generations, and a single system is now capable of producing more than 15MW of 200-mm wide polycrystalline silicon sheet per year. This material is being used to produce large-area APx-8™ solar cells, which are 208 mm x 208 mm on an edge and produce more than 4 W each.

1. Introduction

APex™ is a relatively new material for the industry, considering the growth method, the relatively high level of impurities, and small grain size. An effort is underway to characterize this relatively new material using an industry – academic – government team. Results indicate that the impact of impurities on solar cell performance needs to be defined for new material.

2. Manufacturing Systems

Recent advances in the development of solar cell manufacturing systems for large-area APex™ polycrystalline silicon sheet material have focused on the following processes [1]:

A. cassette-less wet chemical surface etching,
B. production-level silicon nitride anti-reflection coatings,
C. co-fired metal contacts,
D. a highly-automated solar cell tester-sorter system with magazine-based wafer handling,
E. edge grinding process for better edge definition and improved yield and
F. in-line wafer tester for quality control.

A single APex™ polycrystalline silicon sheet generation system now is capable of producing 200-mm wide sheet at more than 3 meters per minute. This sheet generation rate is used as the basis for designing a single-thread solar cell manufacturing production line with an annual capacity of more than 15MW of large-area APx-8™ solar cells.

Previously we have described our development of continuous rapid thermal diffusions using IR belt furnaces and cassette-less diffusion oxide etching using in-line wet chemical process systems [2]. These processes are in place in production running at over 1,000 wafers/hr without the use of cassettes. All of the production systems reviewed here have throughput targets that are matched to the capacity of an APex™ sheet growth generation system.

A. Caustic Surface Etching

Development of the continuous caustic etching tool has now progressed through two prototype systems that were used to demonstrate the in-line concept, demonstrate the feasibility of stack to stack processing, and to investigate specific materials and components of the system. The first production-scale in-line surface etch system is shown in Figure 1. Four APx-8™ wafers are placed across the width of the conveyor. The caustic etching tank in this system is approximately 550-cm long, and it is followed by two immersion acid-rinse sections that are similar to the modules that are used in the diffusion oxide etching system. The wafers are also thoroughly rinsed and dried before exiting from the caustic etching system.

Figure 1. The caustic surface etching system for large-area APex™ polycrystalline silicon wafers.

Compared to a batch-based process in open hoods, this closed system can maintain significantly higher etch solution temperatures and better uniformity, and this has resulted in higher etching rates. Better control has allowed the level of silicon removed to be reduced 40%. Containment of the etching solution within the system has virtually eliminated operator exposure to the etchants used. This system was qualified and put into production use in Fall 2002. The process has demonstrated a production capacity for surface etching silicon wafers of more than 1,000 APx-8™ wafers per hour.

B. PECVD Silicon Nitride Coating

During the third quarter of 2001 AstroPower installed the first commercially available remote-plasma CVD silicon nitride system designed to coat large-area solar cells at production volumes. The PECVD coating systems are quasi-continuous in-line systems with three separate vacuum chambers. A matrix of wafers are placed in large carriers that travel horizontally through the system. The plasma is energized by linear 2.45 GHz microwave sources, which provide excellent plasma conditions (that is, high charge carrier concentrations and low ion- and electron-energies).

Presently, AstroPower has three units in operation with a combined capacity of over 1,500 APx-8™ solar cells per hour.

Figure 2. In-line, large-area microwave-plasma CVD system for silicon nitride deposition. Each wafer carrier accommodates 16 APx-8™ solar cells, and the system has a throughput of more 600 solar cells per hour.

C. Co-Fired Contact Metallization

To realize the full value of the grain boundary and defect passivating qualities of the PECVD silicon nitride coating, a fire-through contact metallization process has been implemented. It has been previously documented in the literature that the temperatures used for firing typical thick film silver conductors through silicon nitride also serve to release entrapped atomic hydrogen from the AR coating layer [3]. It is this hydrogen that is thought to give the surface and bulk passivation characteristic of this technology. The production process sequence for contact firing was significantly revised to take advantage of the passivation potential of the silicon nitride coating.

A new wide belt (96 cm) IR furnace was installed for the co-fire contact firing process. Cells are fired in a four-wide configuration with the front metallization facing upwards. This eliminates the final drying step, and cells can be placed directly onto the belt after printing. The nominal belt speed of the furnace is 1.3 meters per minute, but it is capable of belt speeds significantly greater than this. The present capacity of the IR belt furnace is 1,300 APx-8™ solar cells per hour.

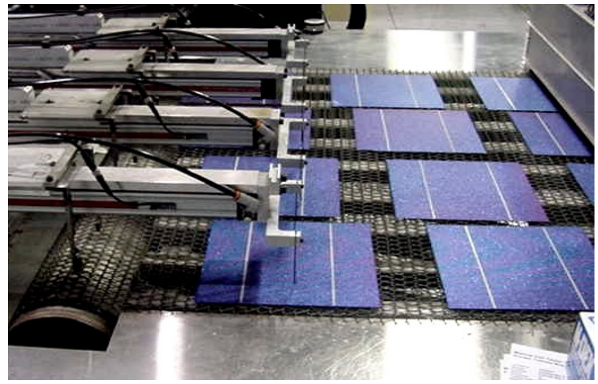

Figure 3. APx-8™ solar cells are unloaded from the front contact screen printer to the furnace conveyor belt in a staggered pattern to smooth furnace loading.

D. Solar Cell Testing and Sorting

A high-speed tester-sorter system for final I-V test of Apx-8™ solar cells, shown in Fig. 4, was developed using several novel concepts to address measurement accuracy and consistency, operational and maintenance costs, and improved material handling.

The unique feature of this solar cell tester system is the use of magazines for transferring large-area solar cells into and out of the system. The magazines are designed to flexibly accommodate full-sized Apx-8™ solar cells, but they can be easily re-configured for half-cell and other cut solar cell sizes. The sorted cells in the magazines are then transferred either to packaging or directly to the unloader of the tabber-stringer system. This is the first process step on the module assembly line.

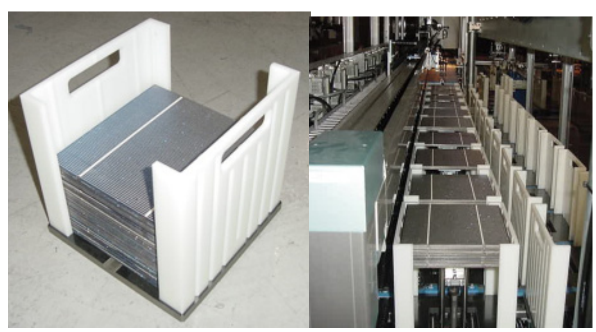

Figure 4. Left side: magazine loaded with APx-8™ solar cells; right side: solar cells are sorted into ten magazines using a linear robot.

E. In-line Wafer Testing

In addition to this I-V tester, an in-line wafer tester is under development. This tester will carry out a series of tests of electrical characteristics and physical dimensions on each wafer prior to entering the production line. This test will provide quality control, increase overall production line yield, and provide feedback to the wafer growth process. Similar to the I-V tester, the process will use magazines for wafer transfer.

F. Wafer Edge Definition

Mechanical yield through the line is highly dependent on the state of the wafer edge. This is well known in the IC industry, and has been shown by other solar cell manufacturers. When an edge resistant to chipping and cracking is formed on each wafer yield increases significantly. To realize this benefit custom built equipment for edge grinding has been designed. This tool is expected to go in to full production in the next 2 months.

3. Materials Characterization

The present conversion efficiency for APex™ solar cells is approximately 80% of those achieved with the industry standard CZ or large grain cast materials. The smaller grain size and the lower purity are the plausible explanations for performance differences. With advances in the understanding of critical high temperature processes, such as gettering, views on impurity requirements have changed. Similarly, conventional grain size limits are shown to be conservative, allowing higher performance than thought possible from smaller grains.

The logical first step is to investigate the impurity content of the wafer and correlate it to performance. This would ideally identify the impurities that have the strongest impact on performance for selective removal. Many methods of chemical analysis were evaluated, and glow discharge mass spectroscopy (GDMS) was chosen as it had the needed detection limits and also the ability to measure impurities in selected regions in the wafer. Methods that determine an "average" measurement over the wafer from front to back give misleading results for APex™ material. Results of the GDMS study were that there is more than enough Fe, W, Al, Mo and Ti to account for all the lifetime degradation in APex™ individually, let alone in total [4]. The level of the impurity did not track lifetime in careful comparisons of material with high and low lifetimes. A similar result was found by a group working with solar materials using NAA [5]. The question then becomes which impurities are detrimental and which are benign.

In an attempt to quantify the role of the impurities, SIMS (Secondary Ion Mass Spectroscopy) depth profiles were taken at the National Renewable Energy Laboratories. That study concluded that carbon precipitates were a major source of recombination activity. Carbon precipitates were also found in TEM studies carried out at both at NREL and at NCSU [6]. Evidence was found of transition metal gettering to these sites.

Work done at North Carolina State University (NCSU) has focused on direct observation of defects through polishing and defect etching [7]. A relationship between oxygen levels and stacking faults was determined.

4. Conclusion

Progress has continued on the realization of a continuous, single-thread, manufacturing line for large area APex™ wafers. Recent efforts have focused on chemical etching, contact firing, and testing. A magazine-based tester-sorter system is being used to explore large-area APx-8™ solar cell handling concepts, and has demonstrated significantly improved material flow from cell production line to module production line and will be expanded throughout the production system for APx-8™ solar cells.

The application of new processing steps and better understanding of defect and impurity interactions is allowing small grain polycrystalline silicon sheet material to produce solar cell efficiencies approaching that of cast material and CZ. To realize the full benefit of working with this highly defected, impure material, a thorough understanding of which impurities and defects are benign and which are limiting performance is needed. Several characterization techniques are being evaluated and their effectiveness in addressing these issues reviewed.

5. Acknowledgements

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6. References

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